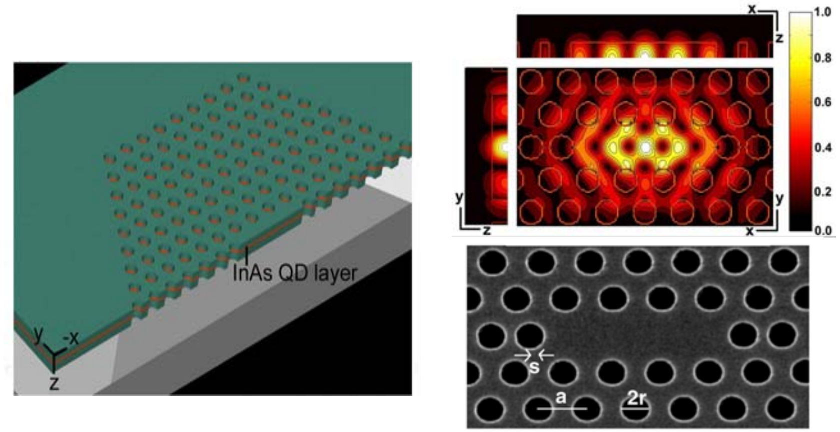
Quantum Dot Photonic Crystal Lasers

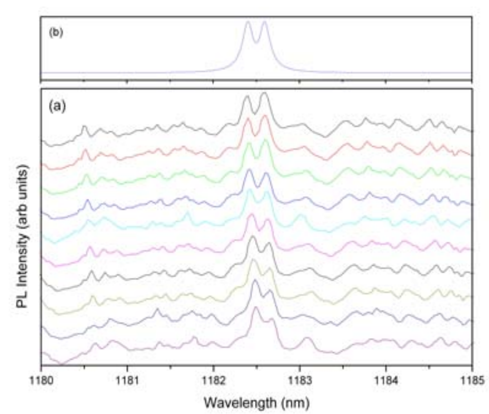
D.G. Deppe (UT Austin), A. Scherer (Cal Tech), DMR 0103134
Experimental observation by H. Gibbs and G. Khitrova (Arizona)

Quantum mechanics predicts that material not only emits light in a continuous spontaneous decay, but can rapidly exchange energy between the material and light field when highly confined. The experimental observance of this phenomenon, called vacuum Rabi oscillation, has been sought in semiconductors for some time.

Researchers from Arizona (Gibbs & Khitrova), using specially designed quantum dot photonic crystals from Cal Tech (Scherer) and UT Austin (Deppe), have reported the first observance of vacuum Rabi oscillations in such a system.



Schematic cross-section (left) of the InAs QD/PC cavity. InAs QDs are embedded at field intensity spot (upper right) in the center of the cavity. The lower right is an SEM photo of the QD/PC cavity.



Scans showing spectral splitting from QD/PC cavity.

Vacuum Rabi oscillations are predicted to occur when the cavity volume is reduced to very small size, and the Q is extremely high. These conditions have been extremely difficult to reach in semiconductors, but have been predicted theoretically possible in quantum dot (QD) photonic crystal (PC) cavities. UT Austin researchers used molecular beam epitaxy to grow high quality InAs QDs in a heterostructure, which was then fabricated into PC cavities by Cal Tech. The PC cavity used a special design to obtain Qs estimated to be >10,000. These samples were then studied under various conditions by Arizona researchers using special optical apparatus designed to measure the emission from very small cavities. Samples were found in which the InAs QDs were favorably located in the center of the PC cavity at an intensity peak of the calculated field. These cavities exhibit not one peak in the luminescence, but two peaks closely spaced and nearly symmetrical. The splitting of the emission into two peaks occurs due to the modulation of the cavity field by an emission and reabsorption by the InAs QD due to trapping of the photon. This phenomenon, called the vacuum Rabi oscillation, is a text book problem in quantum mechanics but heretofore not oberved experimentally in a QD PC due to the need to obtain very high Q with very small volume, and correct placement of a high quality InAs QD. A letter describing the observation has been submitted to the journal Nature.

This observation can open the door to fully quantum mechanical optoelectronic devices based on semiconductor QDs placed in PC cavities. It demonstrates that the fully quantum mechanical regime of light/matter interaction can be achieved, paving the way for new types of quantum mechanical oscillators in semiconductors.

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Education:

Quantum dots and photonic crystals enable scaling of semiconductor photonic devices to their minimum dimensions. Graduate students from UT Austin collaborate with those from Cal Tech to use nanostructure crystal growth and nanolithography to apply the latest fabrication technologies to fabricate the quantum dot photonic crystal cavities. These graduate students have produced the first QD PC lasers, and now the first QD PCs to exhibit vacuum Rabi oscillations.

Outreach:

Profs. Gibbs & Khitrova from Arizona have been in pursuit of the experimental observation of vacuum Rabi oscillations for the last several years. Predicted theoretically possible in QD PCs, it was only recently demonstrated when graduate students from Arizona, unfunded by this NSF NIRT program, used specially designed QD PCs from the UT/Cal Tech NIRT program to demonstrate the world’s first vacuum Rabi oscillations in a QD PC.

UT Austin and Cal Tech have been working on design and fabrication of quantum dots and photonic crystals for several years. In this NIRT program the two schools teamed up to combine the QD and PC technologies to demonstrate new types of devices, especially lasers, and to apply new nanolithography techniques to QD and PC fabrication. The NSF NIRT program has produced the world's first QD PC lasers, demonstrating the viability of combining the two technologies. It has now also, with the collaboration of Arizona, produced the first observation of vacuum Rabi oscillations in QD PC cavity.

Arizona has not been funded on this program, and was not part of the original proposal. The work was made possible because of Arizona's expertise in the experimental studies of the quantum optical response from semiconductors, and some rather tenacious experimental study on their part.

We believe this demonstration represents an important milestone in the field of semiconductor physics and nanotechnology.